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**Role of Computational Fluid Dynamics in
Unsteady Aerodynamics for Aeroelasticity**

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Introduction

In the last two decades, there have been extensive developments in computational unsteady transonic aerodynamics (ref. 1). Such developments are essential since the transonic regime plays an important role in the design of modern aircraft. Consequently, there has been a large effort to develop computational tools with which to accurately perform flutter analysis at transonic speeds. In the area of Computational Fluid Dynamics (CFD), unsteady transonic aerodynamics are characterized by the feature of modeling the motion of shock waves over aerodynamic bodies, such as wings. This modeling requires the solution of nonlinear partial differential equations. At the present time, the most advanced codes such as XTRAN3S, the Air Force/NASA code for transonic aeroelastic analysis of aircraft, use the transonic small perturbation (TSP) equation (ref. 2). Currently XTRAN3S is being used for generic research in unsteady aerodynamics and aeroelasticity of almost full aircraft configurations (ref. 3). Use of Euler/Navier Stokes equations for simple typical sections has just begun. In comparison, for steady flows, Euler/Navier Stokes equations are being used for wing-bodies and complex separated flows (ref. 4). A brief history of the development of CFD for aeroelastic applications has been summarized in figure 1. The present paper summarizes the development of unsteady transonic aerodynamics and aeroelasticity at NASA-Ames in coordination with Air Force, other NASA centers and industries since 1978.

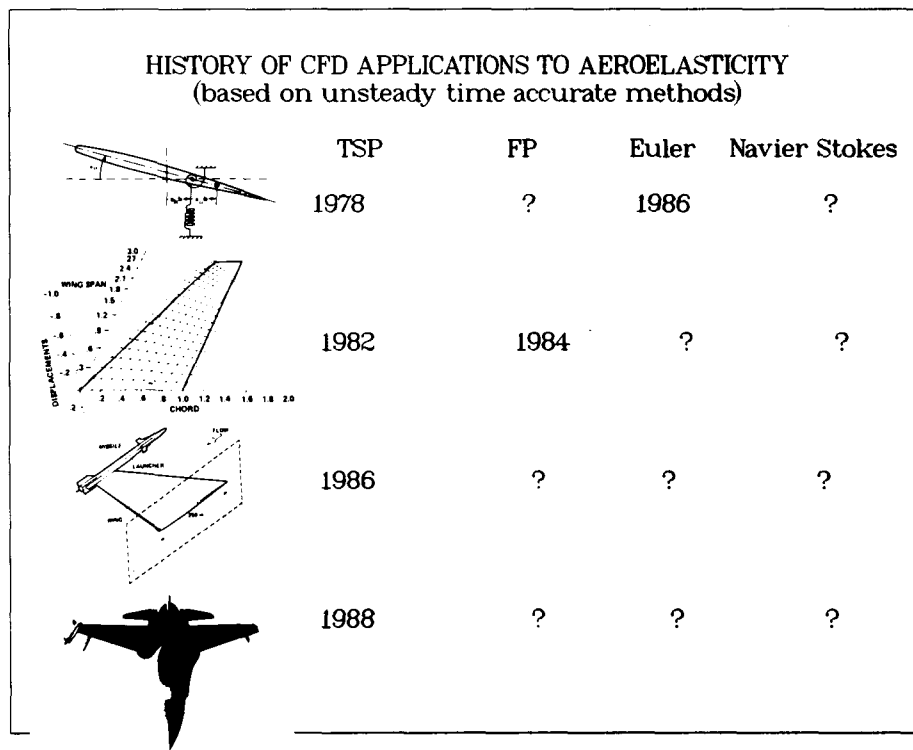


FIGURE 1

Need for Time Accuracy for Aeroelastic Calculations

Transonic aeroelasticity is a highly coupled phenomenon between structures and fluids due to flow nonlinearities. The presence of moving shock waves in the transonic flows further intensifies this coupling and leads to several non-classical aeroelastic phenomenon such as a dip in the flutter boundary curve. In order to make accurate computations in transonic aeroelasticity, it is important to use time accurate methods. The first efficient time accurate method of solving unsteady transonic flows was developed for airfoils using the TSP equations and was implemented in the code LTRAN2 (ref. 5). Based on LTRAN2 several improved codes have been developed and are in routine use for transonic aeroelastic computations of typical sections. A time accurate way of simultaneously integrating unsteady transonic aerodynamics and structural equations of a typical section was first presented in reference 6. From figure 2, taken from reference 6, it can be seen that time linearized computations based on the indicial method and harmonic method fail to predict the neutral stability condition. On the other hand the computations based on the time accurate method succeed. Though the time linearized techniques are sometimes computationally more efficient than the time accurate techniques, one should watch for the non-physical solutions from time linearized methods (indicial, UTRANS2-harmonic method) as shown in figure 2. In this paper several results from time accurate transonic aeroelastic calculations will be presented.

IMPORTANCE OF TIME ACCURACY IN AEROELASTICITY

• RESULTS ARE FROM TIME ACCURATE ADI ALGORITHM

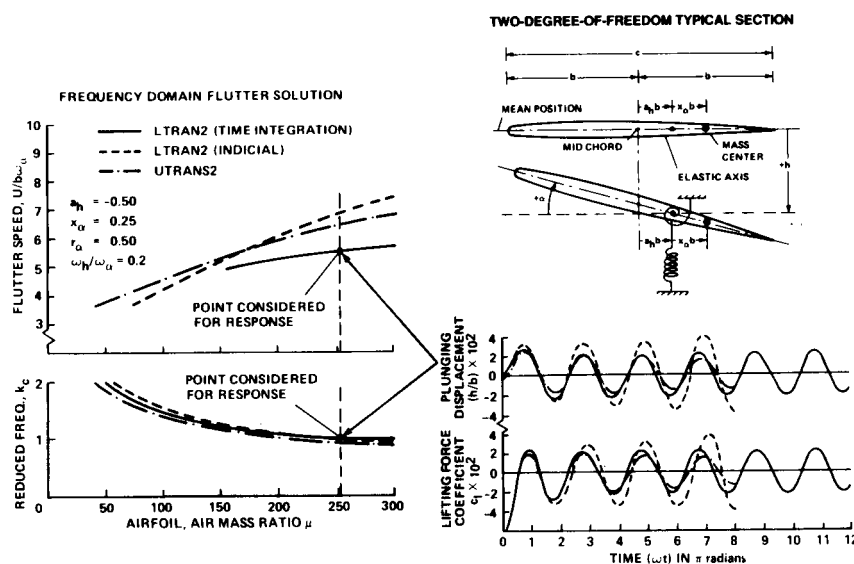


FIGURE 2

Time Accurate Unsteady Calculations of Rectangular Wings

The successful development of the two-dimensional code LTRAN2, which employs an alternating-direction-implicit(ADI), finite-difference scheme, and the availability of faster computers with more memory, made possible the development and use of three-dimensional unsteady transonic aerodynamic codes. LTRAN3, the earlier low-frequency version of XTRAN3S was developed for time accurate calculations (ref. 7). The time accuracy of this code was validated against unsteady experimental data in reference 8. Figure 3 shows the magnitude and the phase angle of the unsteady pressures for a rectangular wing oscillating in its first bending mode. Time accurate computations have accurately captured the effects of unsteady motion of the shock wave. The rise in the phase angle behind the shock wave, which is one of the salient features of the unsteady transonic flow, has been predicted accurately by the alternating direction implicit scheme using the Murman-Cole switch incorporated in LTRAN3. This code was successfully applied to compute the flutter boundaries of rectangular wings by using coupled (ref. 7) and uncoupled (ref. 8) methods. Figure 3, shows the good comparison of unsteady pressures and flutter boundary computed from LTRAN3 with the experiment and NASTRAN, respectively.

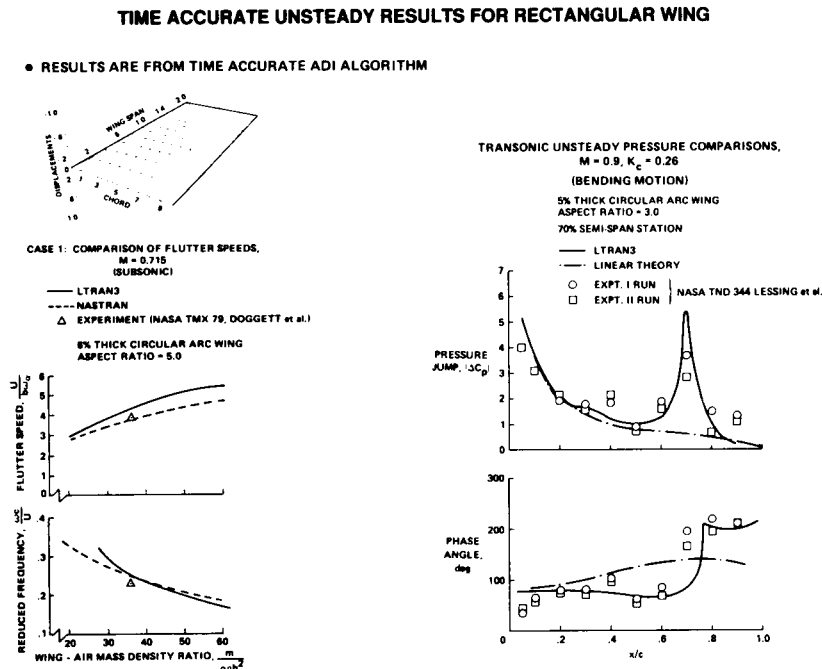


FIGURE 3

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Transonic Aeroelasticity of a Transport Wing

The successful aerodynamic and aeroelastic computations for rectangular wings lead to further applications for more practical configurations. At the same time, the capability of LTRAN3 was extended to account for integration with structures and also high frequency terms. The successful time integration method developed in reference 3 was implemented in XTRAN3S. Using this code, aeroelastic computations were made for a Japanese transport wing and results were compared with the experiment (ref. 9). Figure 4 shows steady pressures and also the flutter boundary curve obtained by using XTRAN3S. During this study several errors in XTRAN3S, such as one in the far span boundary conditions, were corrected. This study also indicated the time step size restriction of XTRAN3S based on sweep angle. Because of the time step size restriction it was not practical to use XTRAN3S for computing flows over low aspect ratio fighter wings. Though several limitations were found in XTRAN3S, this study on a practical wing configuration with favorable comparison with the experiment showed the potential of the code for further development.

TYPICAL TRANSPORT WING

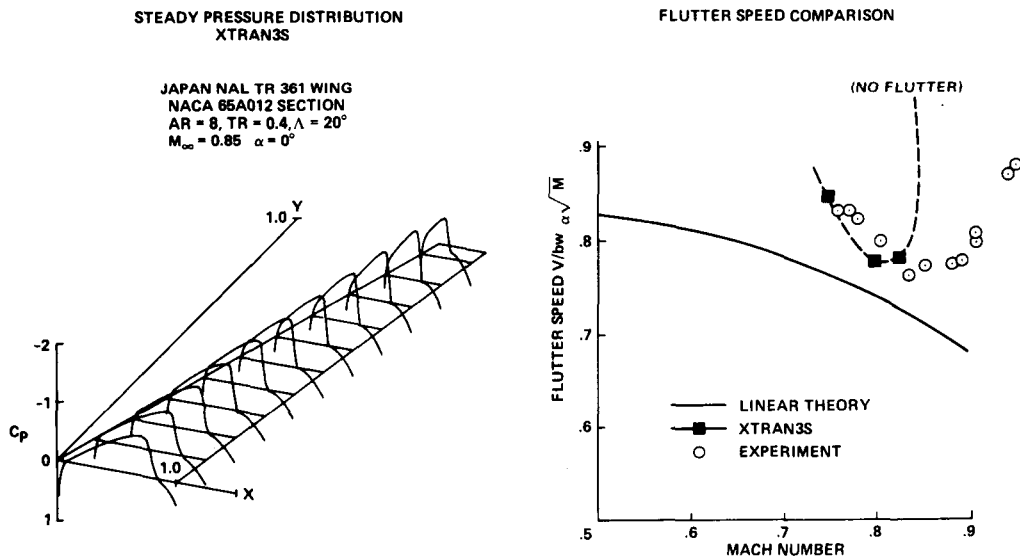


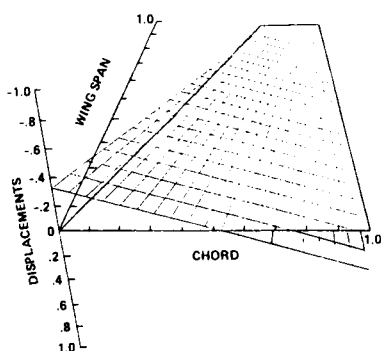
FIGURE 4

Unsteady Transonics of Fighter Wings

Research was further conducted to study the time step size restriction of XTRAN3S. Detailed studies showed that conventional shearing transformation used in XTRAN3S yielded computations that were numerically unstable. The physical grid was dependent upon the planform and was highly skewed for low aspect ratio fighter wings. To correct this, a new modified coordinate transformation technique was developed in reference 10. This modified transformation removed the skewness in the physical grid and led to computations that are stable, fast and accurate. It was first implemented in XTRAN3S-Ames(ATRAN3S), a parallel NASA Ames version of XTRAN3S. Using the modified transformation, for the first time, successful unsteady computations were made for the F-5 fighter wing in the transonic regime. Figure 5 shows the unsteady modal motion and the corresponding unsteady pressures of the F-5 wing at a transonic Mach number of 0.9. Theory compares very well with the experiment. The success of the modified shearing transformation was first reported by the present authors in '1983 Symposium on Transonic Unsteady Aerodynamics and Aeroelasticity and it was implemented in other versions of XTRAN3S.

TYPICAL FIGHTER WING

UNSTEADY MODAL MOTION
F-5 WING, FREQUENCY = 40 Hz
PITCHING ABOUT 50% ROOT CHORD



F5 WING
AR = 2.98
TR = 0.31
LE SWEEP = 32°

NLR EXPERIMENT
□ REAL
△ IMAGINARY

ATRAN3S, $\Delta T = 0.01$
— REAL
--- IMAGINARY

TRANSONIC UNSTEADY PRESSURES
M = 0.90, $f = 40$ Hz, $\alpha = 0^\circ$
MODIFIED TRANSFORMATION

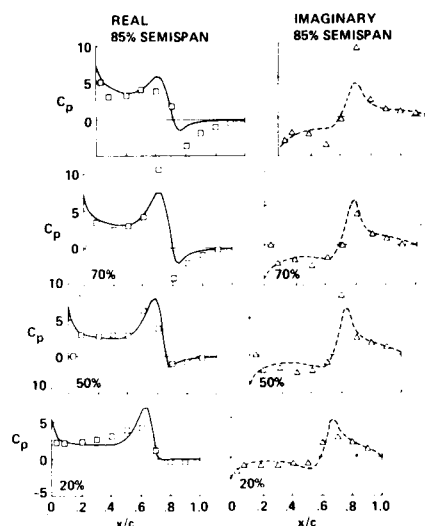
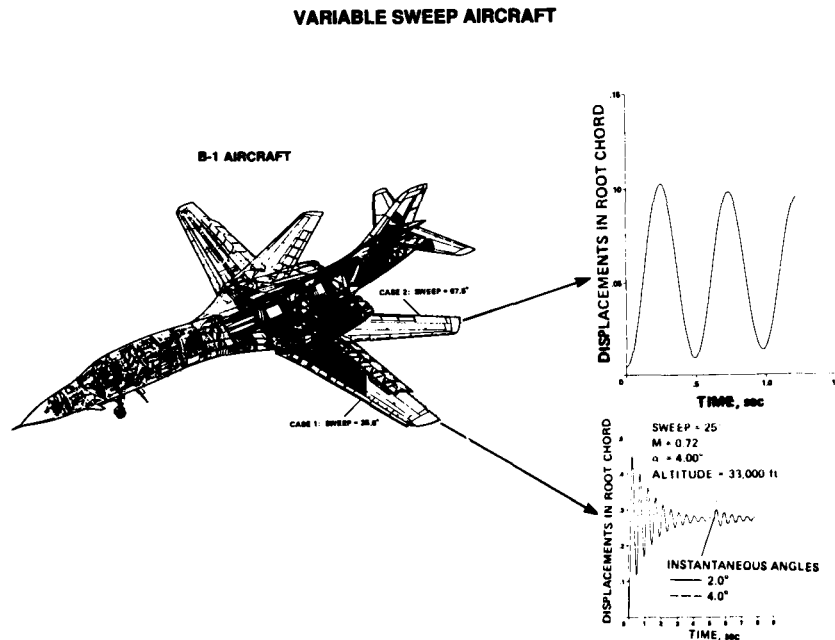


FIGURE 5

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Transonic Aeroelasticity of Variable Sweep B-1 Wing

The variable sweep B-1 wing has been observed to undergo angle of attack dependent aeroelastic oscillations in both flight and wind tunnel tests. These oscillations were more significant at high sweep angles. Motivated by these observations, the flow over the B-1 wing was studied computationally, including the aeroelastic response of the wing. In the low sweep case, the comparisons demonstrated the capability of XTRAN3S-Ames to properly simulate the flow in the presence of shock waves. In the high sweep case, where the sweep angle is equal to 67.5° the comparisons at a low angle of attack demonstrated the capability of the modified shearing transformation to properly simulate the flow at an extreme sweep angle. Computations at the high sweep case for a higher angle of attack at which oscillations were observed did not show any shock waves. Their absence lends support to a new hypothesis that the observed oscillations at the high sweep angle are separation induced oscillations(SIO) due to the presence of leading edge separation vortices and not due to shock induced oscillations as previously proposed before this study. Figure 6 shows the aeroelastic responses at 25° and 67.5° sweep angles. Low damping at high sweep as predicted by XTRAN3S-Ames might have made the wing susceptible to the observed oscillations. Details are given in reference 11. This research demonstrated an important application of time accurate CFD to a crucial practical problem.



Transonic Aeroelasticity Wings with Tip Stores

The presence of tip stores influences both aerodynamic and aeroelastic performances of wings. Such effects are more pronounced in the transonic regime. One of the major advantages of TSP equations is the simplicity of adding new geometry capability to the finite difference grid. As a result, transonic aeroelasticity of wings with tip stores was studied by a theoretical method using the TSP equations coupled with modal structural equations of motion. This new capability was added to XTRAN3S-Ames. Unsteady aerodynamics on the oscillating F-5 wing with a tip missile compared well with the experiment. Aeroelastic computations on a typical rectangular wing indicated that tip store unsteady aerodynamics can make the wing aeroelastically less stable. Aeroelastic computations were also made for a typical fighter wing with a tip store. Computations showed that it is important to account for the aerodynamics of the tip store particularly in the transonic regime where the tip store can make the wing aeroelastically less stable. Details of this work are presented in reference 12. Figure 7 shows the effect of a tip missile on the aeroelastic response of a fighter wing. The unsteady aerodynamic forces of the tip missile decreases the aeroelastic damping of the wing response.

EFFECT OF TIP MISSILE ON FIGHTER WING RESPONSE

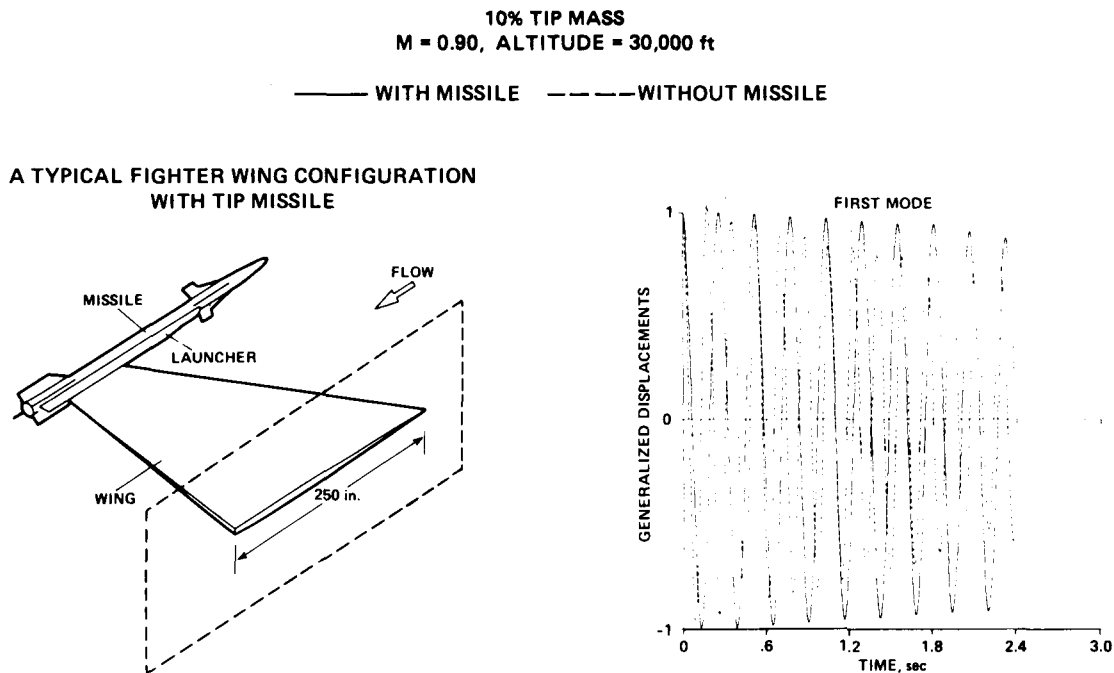


FIGURE 7

An Integrated Approach for Aeroelasticity of Actively Controlled Wings

Use of active controls is important for future aircraft which will tend to be more flexible for high maneuverability. So far, the theoretical aeroelastic studies with active control surfaces have been restricted to the linear subsonic and supersonic regimes. In the non-linear transonic flows, the combined effect of the shock wave and the flow discontinuity due to the presence of the hinge line of the control surface can have a strongly coupled influence on aeroelastic performances of wings. To study such a strongly coupled phenomenon, an integrated approach was developed and has been implemented in XTRAN3S-Ames. It is noted that to study the coupling of complex physical systems like non-linear flows and wing structures, it is important to use well understood equations and solution procedures such as those used in XTRAN3S. Studies showed that shock waves play an important role in active controls and the control laws which do not account for strong coupled phenomena of fluids and structures may not be effective in the transonic regime. Details are presented in reference 13. Figure 8 shows the effect of the active control surface on the twisting modal response of a typical fighter wing. Since the present study is in the time domain, it can be used as a "numerical flight simulator" to complement wind tunnel and flight tests.

EFFECT OF CONTROL SURFACE ON RESPONSES OF FIGHTER WING CONTROLLING THE TWISTING MODE

$M = 0.90$, $Q = 2.476$ psi, $GAIN = 40.0$
TWISTING MODE

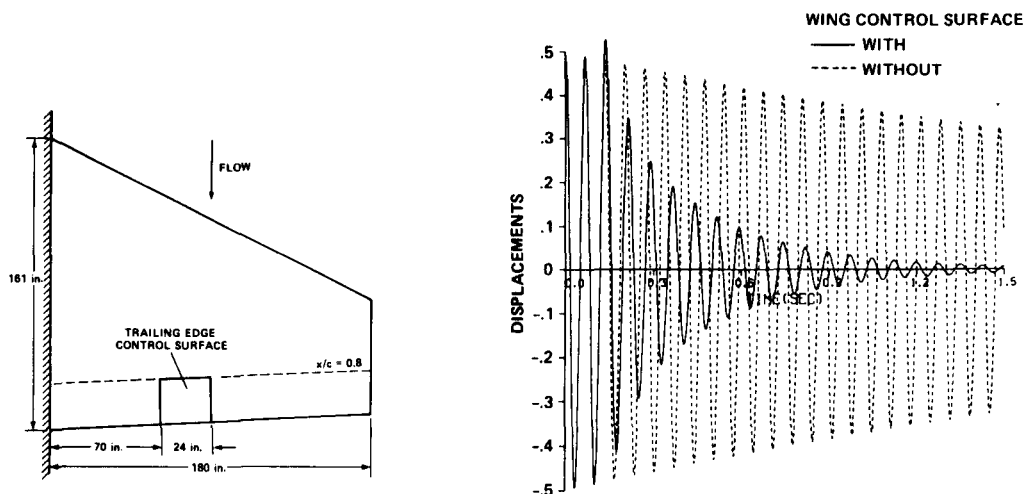


FIGURE 8

Unsteady Transonics of Wings at Supersonic Freestreams

Flow remains nonlinear and transonic in nature for Mach numbers slightly above one. As a result, rapid variations in aerodynamic forces can still occur due to unsteady motions of the wing. Therefore it is important to study the aeroelastic characteristics at low supersonic freestream conditions since critical aeroelastic phenomenon similar to that for transonic freestream conditions can still occur. Supersonic freestream capability was first implemented in the transonic code ATRAN2 (ref. 14), the improved version of LTRAN2. This required the use of different far field boundary conditions than those used for transonic freestream conditions. Due to the lack of manpower and need, no effort was made to implement these modifications into early versions of XTRAN3S. Now there is a need for time accurate aeroelastic computations at supersonic freestreams for advanced fighter aircraft. In this work the capability of XTRAN3S-Ames has been extended to handle supersonic freestream conditions. The far field boundary conditions were modified following the approach given in ref. 13 which is based on the propagation of pressure waves along the flow characteristics. Successful steady and unsteady computations were made for the rectangular and fighter wings at supersonic freestream conditions. Figure 9 shows the good comparison of unsteady pressures computed from XTRAN3S with the experimental data at $M = 1.3$. This new capability is being incorporated in the official XTRAN3S with wing body capability.

F5-WING, $M = 1.33$, $\alpha = 0^\circ$, $k = 0.396$ (40 Hz)

• TIME ACCURATE ADI COMPUTATIONS

UNSTEADY MODAL MOTION
F-5 WING, FREQUENCY = 40 Hz,
PITCHING ABOUT 50% ROOT CHORD

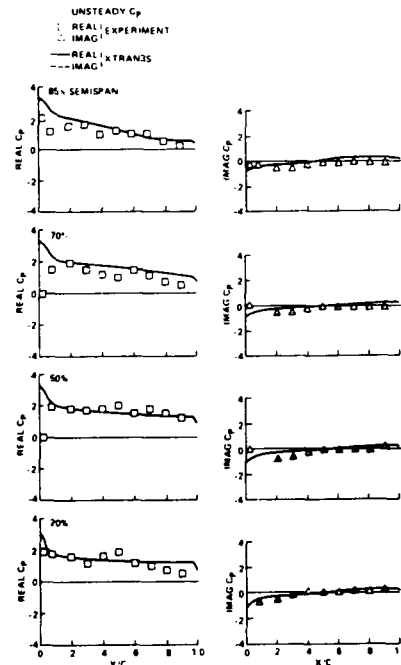
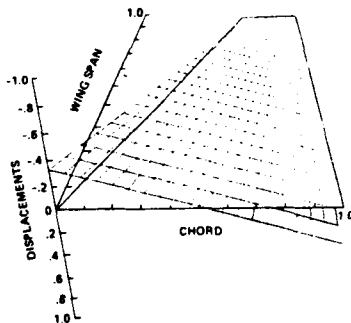


FIGURE 9

Unsteady Transonics of Full-Span Wing-Body Configurations

In the development of CFD it appears that there is more emphasis on using new equations and methods than on adding the geometry and flow physics capabilities. For example, limited effort has been put into extending the powerful TSP theory for unsteady computations of full aircraft, though the steady wing-body computations using TSP were done a decade ago. The presence of a body influences both the aerodynamic and aeroelastic performance of wings. Such effects are more pronounced in the transonic regime. To accurately account for the effect of the body, particularly when the wings are experiencing asymmetric modal motions, it is necessary to model the full configuration in the nonlinear transonic regime. In this study, full-span wing-body configurations are simulated for the first time by using the unsteady TSP equations and it has been incorporated in XTRAN3S-Ames. The body geometry is modeled exactly as the physical shape, instead of as a rectangular box, which has been done in the past. Steady pressure computations for wing-body configurations compare well with the available experimental data. Unsteady pressure computations when the wings are oscillating in asymmetric modes show significant influence of the body. The details are given in reference 15. Figure 10 shows steady pressures on the body (comparing well with the experiment) and also the effect of asymmetry on the unsteady lifting forces of the wing.

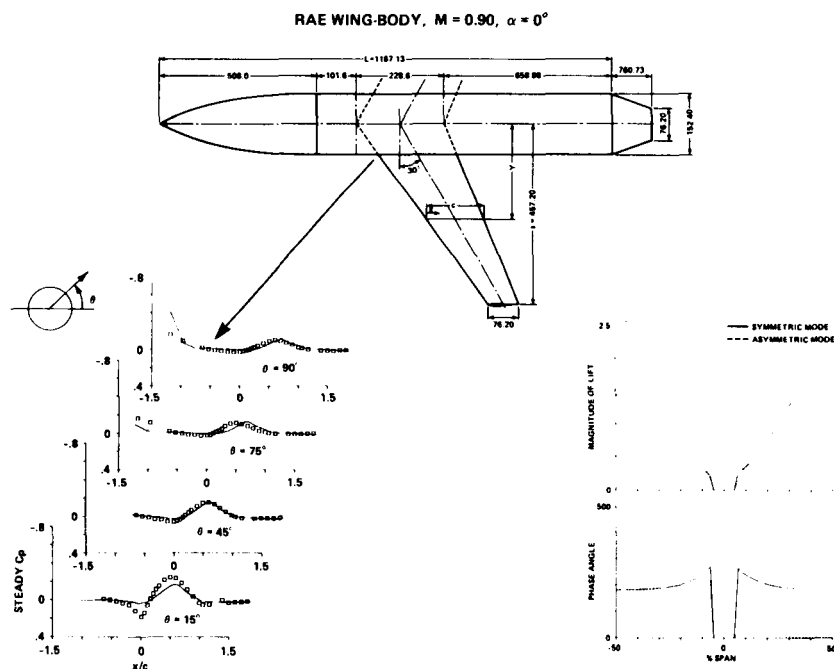


FIGURE 10

A New Algorithm for Unsteady Euler Equations

One of the most successful ideas used in the calculation of transonic flows is the one of Murman-Cole to use different types of differencing for the regions of subsonic and supersonic flows. Central differencing is used in subsonic regions of the flow and upwind differencing is used in supersonic regions of the flow. This change of the algorithm takes into account the fundamentally different characteristics of subsonic and supersonic flows. The previous section of this paper has shown the successful application of the Murman-Cole switch modified by Jameson's rotated differencing scheme to unsteady transonic flow computations on wing-body configurations. Motivated by the success of the type dependent differencing for potential equations, a similar method has been developed (ref. 16) for the Euler equations. This new algorithm uses flux vector splitting in combination with the concept of rotating the coordinate system to the local streamwise direction. The flux vector biasing is switched from upwind for supersonic flow to downwind for subsonic flow. Several one-dimensional calculations for steady and unsteady transonic flows demonstrated the stability and accuracy of the algorithm. Unsteady results were demonstrated for an airfoil whose thickness varies in time. Figure 11 shows the pressure coefficient plots for three times at which the shock wave is increasing in strength and time accurately moving downstream.

UNSTEADY EULER ALGORITHM FOR TRANSONIC FLOW

- NEW ALGORITHM IS BASED ON ADI, FLUX SPLITTING, SWITCHING AT SHOCKS, AND ROTATING DIFFERENCING

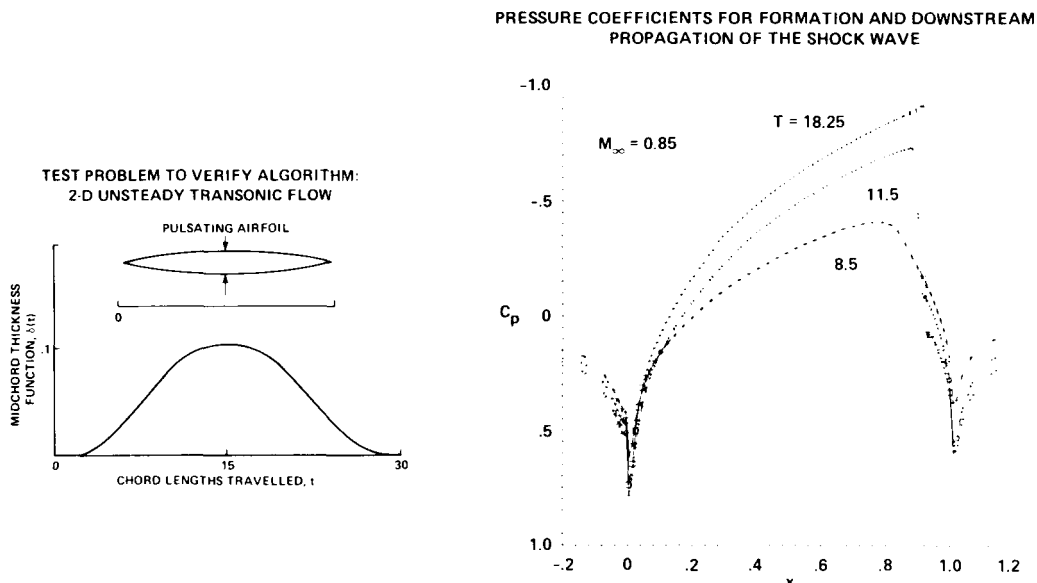
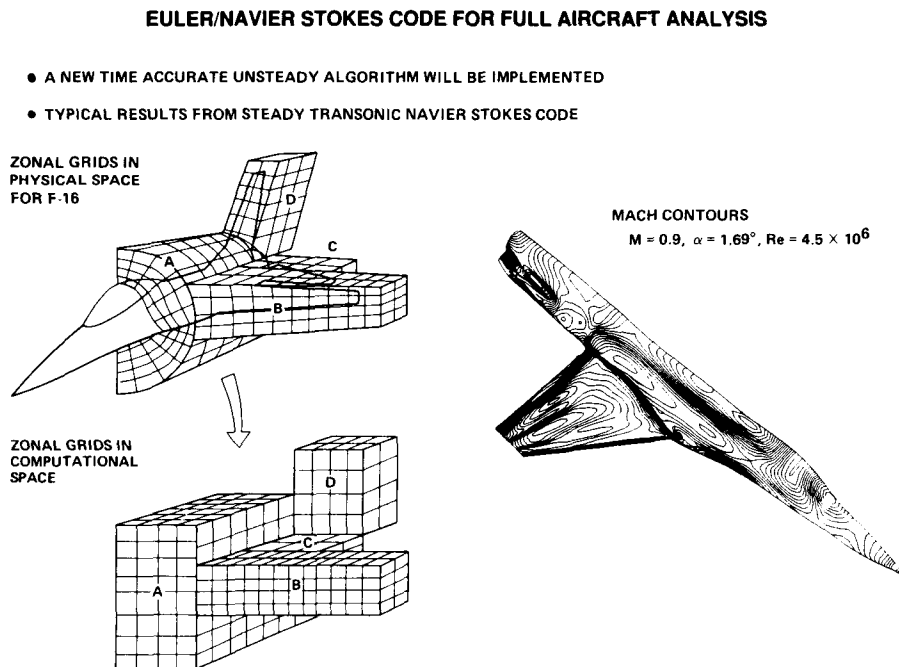


FIGURE 11

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Future Directions and Concluding Remarks

Since about 1978 to date, CFD for aeroelasticity has progressed from solving simple airfoils to almost complete aircraft by using TSP theory. Now industry has a computational tool such as XTRAN3S to simultaneously solve structures and aerodynamics for transonic flows at small angles of attack. Most of the aeroelastic phenomena such as flutter occurs at small angles of attack. As illustrated in this paper, time accurate simultaneous solution of structures and aerodynamics is essential to properly understand the physics of real world aeroelastic problems. The computational efficiency of XTRAN3S has been improved by a factor of about 100 since its first release. The present version, 1.10, of XTRAN3S can make time accurate unsteady transonic computations on fighter wings such as the F-5 in about 10 minutes of CRAY-XMP time. XTRAN3S can further be applied to investigate practically important time dependent aeroelastic phenomenon such as the one illustrated for active controls in this paper. During the last decade CFD without structural coupling has advanced fairly well to the use of Euler/Navier Stokes equations. This has lead to the development of codes such as TNS, a Transonic Navier Stokes code for full aircraft analysis(ref. 4). However, these developments have been mostly restricted to steady computations. New algorithms are being developed to make time accurate unsteady computations(ref. 16). These new tools along with other CFD techniques, such as the zonal grid approach developed for the TNS code(see Figure 12 for typical steady results), need to be extended for aeroelastic computations of full aircraft with complex flows.



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